

APPLICATION FOR
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SPECIFICATION

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Title of the Invention: OPTICAL SWITCH FOR COMPENSATING FOR
DEGRADATION OF OPTICAL-COUPLING
CHARACTERISTIC

099503 40704

Background of the Invention

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A wavelength-division multiplexing (WDM) system is being developed and commercialized as a communications system for rapidly increasing the transmission capacity. To connect WDM systems and to organize a wide photonic network, a ring type network for connecting a plurality of devices in a loop shape is being studied. In this network, as the scale of a network is extended, a transmitting data amount in a loop is extremely increased. Thus, a mesh type network for connecting a plurality of devices in a mesh shape is also extensively studied.

20 The key technology of such a network organization
is a large-scale optical switch for switching a lot of
input/output fibers. In a ring type network or a
point-to-point system, an electric switch is used to
extract a low-order group signal from a node. By replacing
25 this electric switch with an optical switch, cost of

a node device can be reduced. Therefore, the implementation of a large-scale optical switch is a major issue in a variety of networks.

Most of currently commercialized optical switches
5 are waveguide type small-scale switches and the switch is composed of an input/output fiber array and a switch element. To extend the scale of a switch element, the yield of a switch cell must be improved. However, since the dimensions tolerance in a manufacturing process is
10 small, it is difficult to improve the yield.

Although an optical loss factor includes both loss in a switch cell and loss in a joint with an input/output fiber, it is difficult to reduce both the loss. For this reason, to extend the scale of a switch element, it is
15 necessary not only to improve the yield by the improvement of the manufacturing process, but also to remarkably improve the element performance.

As a conventional art, there is also a configuration for spatially switching light. In this case, for example,
20 if a reflection mirror is used as an optical path modifying element, there is no problem in performance, such as an on/off ratio, crosstalk and the like, which are problems in a waveguide type switch. However, since the volume of a switch increases, it is difficult to extend
25 the scale from the viewpoint of size.

To break the deadlock, recently a semiconductor manufacturing technology for manufacturing this spatial switch in small size has been developed. This technology is called a "micro-electro-mechanical system (MEMS) and in particular the technology applied to the optical field is also called an "optical MEMS". According to this technology, a micro-mirror is manufactured on a substrate by a semiconductor manufacturing technology and desired input and output can be spatially coupled by three-dimensionally inclining this mirror by static electricity.

Fig. 1A shows a MEMS micro-mirror. The size of a round mirror 11 is approximately several hundred microns and the inclination of this mirror 11 is adjusted by the static electricity of four electrodes 12 around the mirror 11. Thus, the output direction of light reflected on the mirror 11 three-dimensionally changes and switching is performed.

Since this spatial switch uses a mirror, the switch is superior to a waveguide type switch in switching performance, and the size is also as small as that of the waveguide type switch. Since in this way, one-input/n-output switching can be spatially performed by such one movable mirror, as shown in Fig. 1B, this switch is called a "three-dimensional MEMS switch".

In Fig. 1B, a movable mirror 13 can output light from one input fiber 14 to one of n output fibers 15. In this case, mirror displacement parameters are two of θ_x representing the x-axis rotation angle of a mirror and θ_y , representing the y-axis rotation angle. By applying prescribed voltages V_x and V_y to the electrodes, the inclination angle of a mirror is changed by a predetermined amount, and switching is performed accordingly.

10 If a large angled displacement amount of this movable mirror cannot be secured, as shown in Fig. 1C, movable mirrors can also be located in two stages. In Fig. 1C, light from the input fiber 14 is reflected on a first-stage movable mirror 16 and is directed to a fixed mirror 17. 15 The light reflected on the fixed mirror is directed to a second-stage movable mirror 18. Then, the light is reflected on the movable mirror 18 and is outputted from one of n output fibers 15. In this case, since the mirror displacement parameters of each movable mirror are two 20 of θ_x and θ_y , the total number of parameters becomes four.

 If an n -input/ n -output switch is configured, n and $2n$ movable mirrors are used in one-stage and two-stage types, respectively.

 However, the conventional optical MEMS switch 25 described above has the following problem.

The rigidity of a mirror used for switching varies depending on the ambient temperature and humidity. Due to this, the voltage-rotation angle characteristic of the mirror can change and an optical-coupling characteristic at the time of switching can degrade accordingly. The degradation of the optical-coupling characteristic includes the reduction of optical-coupling efficiency, crosstalk to another channel and the like.

The optical-coupling characteristic at the time of switching can also be degraded by the mechanical vibration of a mirror and the like. The degradation of an optical-coupling characteristic caused by such factors must be by any means compensated for.

Summary of the Invention

It is an object of the present invention to provide a MEMS switch for compensating for the degradation of an optical-coupling characteristic in a node device constituting a photonic network.

The optical switch of the present invention comprises a mirror, the inclination angle of which varies depending on an application voltage, a driver device, an oscillation device, a superimposition device, a detection device and a control device. The driver device

applies an application voltage to the mirror, and the oscillation device generates an additional signal of a prescribed frequency. The superimposition device superimposes the additional signal on the application
5 voltage, and the detection device detects an signal component of the prescribed frequency from light reflected on the mirror. The control device performs control of the application voltage based on the detected signal component.

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Brief Description of the Drawings

Fig. 1A shows a micro-mirror;

Fig. 1B shows the configuration of a one-stage type mirror configuration;

15 Fig. 1C shows the configuration of a two-stage type mirror configuration;

Fig. 2 shows the basic configuration of an optical switch according to the present invention;

Fig. 3 shows an η -V characteristic;

20 Fig. 4A shows drift in the positive direction;

Fig. 4B shows drift in the negative direction;

Fig. 5 shows the configuration of the first optical switch;

25 Fig. 6 shows the circuit of the first optical switch;

superimposition device 23 superimposes the additional signal on the application voltage, and the detection device 24 detects a signal component of the prescribed frequency from light reflected on the mirror 20. The control device 25 performs control of the application voltage based on the detected signal component.

The mirror 20 corresponds to, for example, a MEMS micro-mirror. The mirror 20 reflects light and generates output light from the optical switch. The superimposition device 23 superimposes the additional signal generated by the oscillation device 22 to the application voltage outputted by the driver device 21. Then, the application voltage on which the additional signal is superimposed is applied to the mirror 20 to drive the mirror 20.

The light reflected on the mirror 20 includes a signal component of the additional signal frequency. This signal component is detected by the detection device 24 and is outputted to the control device 25. The control device 25 performs control of the driver device 21 in such a way that the application voltage can increase/decrease in accordance with the value of this signal component.

According to such an optical switch, the frequency component of the additional signal that appears in reflected light varies depending on the fluctuations

of an optical-coupling characteristic. Thus, by increasing/decreasing an application voltage based on the change of this element, the fluctuations of the optical-coupling characteristic can be compensated for.

5 The driver device 21 shown in Fig. 2 corresponds to, for example, the driver circuit 46 shown in Fig. 5, which is described later, the driver/control circuits 63 and 64 shown in Fig. 7, which are described later, and the driver/control circuits 103, 104, 113 and 114,
10 which are described later.

 The oscillation device 22 shown in Fig. 2 corresponds to, for example, the low-frequency oscillation circuit 48 shown in Fig. 5, the low-frequency oscillation circuits 65 and 66 shown in Fig. 7 and the
15 low-frequency oscillation circuits 105, 106, 115 and 116 shown in Fig. 9.

 The superimposition device 23 shown in Fig. 2 corresponds to, for example, the low-frequency superimposition circuit 45 shown in Fig. 5, the
20 low-frequency superimposition circuits 61 and 62 shown in Fig. 7 and the low-frequency superimposition circuits 101, 102, 111 and 112 shown in Fig. 9.

 The detection device 24 shown in Fig. 2 corresponds to, for example, the low-frequency detection circuit
25 44. The control device 25 shown in Fig. 2 corresponds

to, for example, the control circuit 47 shown in Fig. 5, the driver/control circuits 63 and 64 shown in Fig. 7, the driver/control circuits 103, 104, 113 and 114 shown in Fig. 9, and the digital control circuit 121 and external storage circuit 122 shown in Fig. 10, which is described later.

The optical-coupling efficiency η for each output fiber (channel) of a MEMS micro-switch can be expressed as follows.

$$\eta = \exp(-\pi^2 \cdot \theta^2 \cdot w^2 / \lambda^2) \quad (1)$$

In the above equation, θ represents the deviation angle between a light beam reflected on a mirror and an output fiber, and is proportional to the deviation of the rotation angle of the mirror. w and λ represents a beam radius and the wavelength of light, respectively.

Since the relation between the rotation angle of a mirror and a voltage applied to an electrode is almost linear, the relation between optical-coupling and a rotation angle can be replaced with the η -V characteristic of optical-coupling efficiency η and a MEMS driving voltage (application voltage) V . This η -V characteristic generally is a one-peak non-linear characteristic. Therefore, a prescribed voltage is applied so as to maximize this optical-coupling efficiency of each output fiber.

Fig. 3 shows an η -V characteristic of an output fiber. In Fig. 3, the unit of η is decibel (dB) and η is the maximum when $V=V_a$. Therefore, if input light is switched to this output fiber, V_a is applied to the electrode. Furthermore, in this preferred embodiment, to detect the drift (deviation) of the η -V characteristic and to compensate for the degradation of output light due to the drift, a low-frequency signal $V_c \cdot \cos(\omega t)$ is superimposed on V_a as an additional signal.

Fig. 4A shows the relation between drift and output light in the case where a low-frequency signal is superimposed on an application voltage. First, as shown by a curve 31, if there is no drift in the η -V characteristic, no low-frequency component appears in an output light signal 34 for an application voltage 33 ($V_a + V_c \cdot \cos(\omega t)$) on which the low-frequency signal is superimposed.

However, if the η -V characteristic drifts in the positive direction (rightward) and a curve 32 is obtained, an output light signal 35 becomes $V_{ma} + V_{mc} \cdot \cos(\omega t)$ and an output light level decreases. Simultaneously, a low-frequency component of the same phase as that of the application voltage appears as a superimposed signal. As shown in Fig. 4B, if the η -V characteristic drifts in the negative direction (leftward) and a curve 36 is

42, a mirror unit 43, a low-frequency detection unit 44, a low-frequency superimposition circuit 45, a driver circuit 46, a control circuit 47 and a low-frequency oscillation circuit 48.

5 The mirror unit 43 comprises a micro-mirror and electrodes, and optical paths 41 and 42 correspond to a path for the input light and a path for the output light, respectively, to and from a switch. The driver circuit 46 generates a prescribed application voltage
10 for directing output light to a prescribed output fiber. The low-frequency oscillation circuit 48 oscillates a low-frequency signal of a prescribed frequency. The low-frequency superimposition circuit 45 superimposes the low-frequency signal from the low-frequency
15 oscillation circuit 48 on the application voltage from the driver circuit 46 and applies the voltage to an electrode of the mirror unit 43.

 The low-frequency detection unit 44 detects a low-frequency component in output light reflected on
20 the mirror 43 and transfers the component to the control circuit 47. The control circuit 47 generates a control signal using both the received low-frequency component and the output signal of the low-frequency oscillation circuit 48 and outputs the control signal to the driver
25 circuit 46. Then, the driver circuit 46 changes the

application voltage based on the control signal.

The optical switch shown in Fig. 5 can be implemented by using an analog circuit and/or a digital circuit. If an analog circuit is used, for example, the circuit configuration shown in Fig. 6 can be obtained.

In Fig. 6, an optical coupler 51, a photo-diode 52 and an amplifier 53 correspond to the low-frequency detection unit 44 shown in Fig. 5. An oscillator 55 corresponds to the low-frequency oscillation circuit 48 shown in Fig. 5. A multiplier 54 (synchronous detector, etc.) and a low-pass filter 56 correspond to the control circuit 47 shown in Fig. 5. A differential amplifier 57 corresponds to the driver circuit 46 shown in Fig. 5, and a coil 58 and a capacitor 59 correspond to the low-frequency superimposition circuit 45 shown in Fig. 5.

The oscillator 55 generates a low-frequency signal of $V_c \cdot \cos(\omega t)$, and the differential amplifier 57 outputs application voltage V_a in a state with no drift. The optical coupler 51 branches output light in the optical path 42, and the photo-diode 52 detects the signal of the branched light. Then, the amplifier 53 amplifies the detected signal and inputs the signal to the multiplier 54.

In this case, as shown in Fig. 4A, if an η -V

characteristic drifts in the positive direction, the output of the amplifier 53 is $V_{ma} + V_{mc} \cdot \cos(\omega t)$. The multiplier 54 multiplies this signal by the output of the oscillator 55 to generate the following signal V_M .

$$\begin{aligned}
 V_M &= \{V_{ma} + V_{mc} \cdot \cos(\omega t)\} \cdot V_c \cdot \cos(\omega t) \\
 &= V_{ma} \cdot V_c \cdot \cos(\omega t) + V_{mc} \cdot V_c \cdot \cos^2(\omega t) \\
 &= V_{ma} \cdot V_c \cdot \cos(\omega t) + 0.5 \cdot V_{mc} \cdot V_c \\
 &\quad + 0.5 \cdot V_{mc} \cdot V_c \cdot \cos(2\omega t)
 \end{aligned} \tag{2}$$

The low-pass filter 56 is designed so as to eliminate the AC component of the signal V_M and to pass only the DC component, and outputs the DC voltage of $0.5 \cdot V_{mc} \cdot V_c$. Similarly, as shown in Fig. 4B, if the η -V characteristic drifts in the negative direction, the DC voltage of $-0.5 \cdot V_{mc} \cdot V_c$ is outputted from the low-pass filter 56. Then, the differential amplifier 57 generates application voltage $V_a + \Delta V_a$, by which the drift is compensated for, by comparing this DC voltage with originally applied V_a .

Since V_{mc} can be considered to be almost proportional to the amount of drift, the absolute value of the output of the low-pass filter 56 is also proportional to the drift amount. Furthermore, if the direction of drift is positive, the output value becomes positive. If the direction is negative, the output becomes negative. Therefore, by controlling an

application voltage using this value, the influence of drift can be compensated for.

The optical switch shown in Fig. 5 is configured so as to perform control of the rotation angle of one of two rotation axes of a mirror. However, if the optical switch simultaneously performs control of the respective rotation angles of two rotation axes, the configuration is as shown in Fig. 7. The optical switch shown in Fig. 7 comprises optical paths 41 and 42, a mirror unit 43, a low-frequency detection unit 44, low-frequency superimposition circuits 61 and 62, driver/control circuits 63 and 64 and low-frequency oscillation circuits 65 and 66. Each of the driver/control circuits 63 and 64 has the functions of both the driver circuit 46 and control circuit 47 that are shown in Fig. 5.

In this case, it is assumed that two mirror rotation axes of the mirror unit 43 are x-axis and y-axis and the rotation angles of these axes are θ_x and θ_y , respectively. It is also assumed that the voltages for performing control of θ_x and θ_y are an x-axis electrode and a y-axis electrode, respectively, and the voltages applied to the electrodes are V_x and V_y , respectively. The low-frequency superimposition circuit 61, driver/control circuit 63 and low-frequency oscillation circuit 65 adjust V_x based on a signal from the

5 If the optical switch shown in Fig. 7 is configured
by an analog circuit, the configuration, for example,
as shown in Fig. 8 is obtained. In Fig. 8, oscillators
73 and 74 correspond to the low-frequency oscillation
circuits 65 and 66. A multiplier 71, a low-pass filter
10 75 and a differential amplifier 77 correspond to the
driver/control circuit 63 shown in Fig. 7, and a
multiplier 72, a low-pass filter 76 and a differential
amplifier 78 correspond to the driver/control circuit
64 shown in Fig. 7. A coil 79 and a capacitor 81 correspond
15 to the low-frequency superimposition circuit 61 shown
in Fig. 7, and a coil 80 and a capacitor 82 correspond
to the low-frequency superimposition circuit 62 shown
in Fig. 7.

In this case, if both η -V characteristics of the
 25 x-axis and y-axis drift, two low-frequency components

of ω_x and ω_y are superimposed on and appear in output light. Therefore, the output of the amplifier 53 is $V_{ma} + V_{mcx} \cdot \cos(\omega_x t) + V_{mcy} \cdot \cos(\omega_y t)$. However, V_{ma} is an output value obtained when $V_x = V_{ax}$ and $V_y = V_{ay}$. The multiplier 5 71 multiplies this signal by the output of the oscillator 73 to generate the following signal.

$$\begin{aligned}
 V_{Mx} &= \{V_{ma} + V_{mcx} \cdot \cos(\omega_x t) + V_{mcy} \cdot \cos(\omega_y t)\} \cdot V_{cx} \cdot \cos(\omega_x t) \\
 &= V_{ma} \cdot V_{cx} \cdot \cos(\omega_x t) + V_{mcx} \cdot V_{cx} \cdot \cos^2(\omega_x t) \\
 &\quad + V_{mcy} \cdot V_{cx} \cdot \cos(\omega_x t) \cdot \cos(\omega_y t) \\
 10 \quad &= 0.5 \cdot V_{mcx} \cdot V_{cx} + 0.5 \cdot V_{mcx} \cdot V_{cx} \cdot \cos(2\omega_x t) \\
 &\quad + V_{ma} \cdot V_{cx} \cdot \cos(\omega_x t) + 0.5 \cdot V_{mcy} \cdot V_{cx} \cdot \cos((\omega_x + \omega_y)t) \\
 &\quad + 0.5 \cdot V_{mcy} \cdot V_{cx} \cdot \cos((\omega_x - \omega_y)t) \quad (3)
 \end{aligned}$$

If this V_{Mx} passes through the low-pass filter 75, the AC component is eliminated and the DC component of 15 $0.5 \cdot V_{mcx} \cdot V_{cx}$ is obtained. This value is regarded to be proportional to the drift amount of the x-axis η -V characteristic and becomes positive/negative corresponding to the positive/negative direction of the drift. The differential amplifier 77 generates 20 application voltage $V_{ax} + \Delta V_{ax}$, by which the drift is compensated for, by comparing this DC voltage with V_{ax} .

Similarly, the multiplier 72 produces signal V_{My} by multiplying the output of the amplifier 53 by the output of the oscillator 74, and the low-pass filter 25 76 outputs a DC voltage corresponding to drift on the

y-axis. Then, the differential amplifier 78 generates application voltage $V_{ay} + \Delta V_{ay}$, by which the drift is compensated for, by comparing this DC voltage with V_{ay} .

According to such a control method, when the number
 5 of parameters to be controlled increases, it is sufficient to prepare so many low-frequency oscillation circuits of different frequencies, driver/control circuits and low-frequency superimposition circuits in accordance with the number of the parameters. For example,
 10 in the case of a switch cell of two-stage mirror configuration as shown in Fig. 1C, it is sufficient that the same circuits as those shown in Fig. 7 are provided in each of the former- and latter-stage mirror units.

Fig. 9 shows the configuration of such an optical
 15 switch of two-stage mirror configuration. The optical switch shown in Fig. 9 comprises optical paths 41 and 42, a low-frequency detection unit 44, mirror units 91 and 92, low-frequency superimposition circuits 101, 102, 111 and 112, driver/control circuits 103, 104, 113 and
 20 114 and low-frequency oscillation circuits 105, 106, 115 and 116.

In this case, the respective rotations of the x-axis and y-axis of the former-stage mirror unit 91 are controlled by application voltages V_{x1} and V_{y1} ,
 25 respectively, and the respective rotations of the x-axis

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circuit 46. Further, the digital control circuit 121 writes the respective values of application voltage V_a and optical-coupling efficiency η in the external memory circuit 122 in a predetermined cycle. Then, the external
 5 memory circuit 122 notifies a device control unit of a node device of those values of the parameters as performance data.

The state of the optical MEMS switch can be estimated by monitoring these two parameters. For example,
 10 if η is kept constant and only V_a gradually increases or decreases, the electrode portion of the MEMS may be degraded. In this case, it is supposed that a required application voltage will exceed the control range sooner or later.

15 Therefore, the threshold (an upper limit and a lower limit) of this value is set in the device control unit and if the threshold value is reached, the device control unit issues a critical alarm. Thus, a user can exchange the electrodes before the electrodes are thoroughly
 20 degraded. Contrary, if only η decreases, the optical-coupling portion may be degraded. In this case too, similarly, exchange is possible before degradation by determining the threshold for issuing an alarm.

Fig. 11 shows one circuit configuration of the
 25 optical switch shown in Fig. 10. The same numerals of

the constituent elements shown in Fig. 11 as those shown in Fig. 6 represent the same constituent elements shown in Fig. 6. A communications LSI (Large-Scale Integration) 131 and a RAM (Random-Access Memory) 132 correspond to the external memory circuit 122 shown in Fig. 10, and an arithmetic circuit 133, a D/A (digital-to-analog) conversion circuit 134 and an A/D (analog-to-digital) conversion circuit 135 correspond to the digital control circuit 121 shown in Fig. 10. An amplifier 136 corresponds to the driver circuit 46 shown in Fig. 10.

The A/D conversion circuit 135 converts the output of the low-pass filter 56 into a digital signal and outputs the signal to the arithmetic circuit 133. The arithmetic circuit 133 calculates an application voltage for compensating for drift based on the inputted signal and outputs a signal corresponding to the voltage value to the D/A conversion circuit 134. The D/A conversion circuit 134 converts the inputted signal into an analogue signal and outputs the signal to the amplifier 136. The amplifier amplifies the signal.

The arithmetic circuit 133 calculates the respective values of both V_a and η , and writes the values in the RAM 132, and the communications LSI 131 notifies the device control unit of the data stored in the RAM 132. A parameter representing optical-coupling loss can

be used instead of η . In the case where a digital circuit is added to the driver/control circuits shown in Fig. 7 or 9, the configuration is similar to that shown in Fig. 10.

5 By the way, since a movable mirror is used for an optical switch, as shown in Fig. 12, there is a possibility of causing resonant vibration. If a completely free round plate is used as a model of a movable mirror, the resonance frequency f_r can be expressed as follows.

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$$f_r = (\lambda^2 \cdot h / 2 / \pi / a^2) \cdot ((E / 3 / (1 - V^2) / \rho)^{0.5}) \quad (4)$$

In the above equation, λ , h , a , E , V and ρ are a mode parameter, thickness, a radius, Young's modulus, a Poisson's ratio and material density, respectively. For example, if $\lambda = 3.2$ (in the case of a basic mode),
 15 $h = 1\mu\text{m}$, $a = 150\mu\text{m}$, $E = 150 \times 10^9 \text{N/m}^2$, $V =$ approximately 0.3 and $\rho = 2 \times 10^3 \text{kg/m}^3$ (in the case of silicon (Si)),
 $f_r = 260 \text{KHz}$ (cycle: $4\mu\text{sec.}$). Since mirrors are actually fixed in four places, the resonance frequency will be higher and be in order of MHz.

20 If this resonance occurs, optical-coupling efficiency vibrates with a resonance frequency, and the quality of output light is degraded. Since the mirror's inclination due to resonance is equivalent to the drift of the η - V characteristic described above, the influence
 25 of the resonant vibration can be compensated for by the

However, if the frequency of a low-frequency signal to be superimposed is lower than a resonance frequency, there is no control, and the start of control delays accordingly. Therefore, the frequency of a low-frequency signal is set higher than a resonance frequency, and simultaneously the circuit is configured in such a way that the time constant of the control system will be small. Thus, high-accuracy control is available.

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